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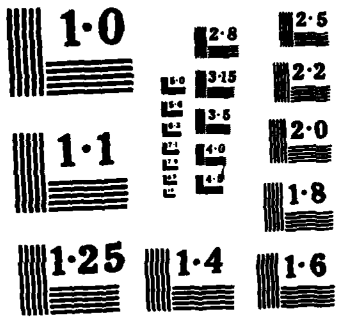

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TECHNICAL REPORT BRL-TR-2690

AN ALGORITHM FOR MONTE CARLO RESTORATION OF BINARY IMAGES

B. Roy Frieden
Csaba K. Zoltani

November 1985

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I. INTRODUCTION

Binary objects arise commonly as the subjects of man-made construction. Examples are a page of print and its variants (handwritten message, license plate on a "getaway" car, etc.), pictures in dot matrix format viewed in closeup, and industrial rods of known material viewed in a tomographic setup.* Alternatively, a user might want to reconstruct a multilevel object as a binary object in order to exaggerate certain features such as edge details.

That an object is binary represents a tremendous amount of a priori information, something that greatly aids in its restoration. A further aid is that often the user knows as well minimal sizes for constituent shapes in the object scene. For example, if many industrial rods (of whatever shape) comprise the object, each might be known to have an area at least as large as value A. If such knowledge can be built into the restoration method, it must also improve the output estimate. Finally, if the method can recognize strangely located points on the periphery of the object's constituent shapes, and place them in more regular positions, this also will help. We report next on an approach that incorporates these kinds of prior knowledge.

II. SCENARIO

We adopt the notation that image data

$$\mathrm{Data}_{ij},\quad i=1,\ldots,\mathrm{Nfield};\quad j=1,\ldots,\mathrm{Nfield}$$

are given, and that the point spread function $s(i,j)$ is known to a good approximation. For simplicity, the space Δx between rows of data is made unity, as is Δy. Quantity i is, in our notation, both a row number and an x-value, and j is a column number and y-value. The image is assumed to be formed from the unknown object Obj_{ij}, $i=1,\ldots,\mathrm{Nfield}$; $j=1,\ldots,\mathrm{Nfield}$ via a convolution

$$\mathrm{Data}(i,j) = \sum_{k=1}^{\mathrm{Nfield}} \sum_{m=1}^{\mathrm{Nfield}} \mathrm{Obj}(k,m)s(i-k,\, j-m) + \mathrm{Noise}(i,j) \qquad (1)$$

for all (i,j). The objective is to retrieve the $\mathrm{Obj}(k,m)$ from this data. Every value $\mathrm{Obj}(k,m) = 0$ or 1, since the object is binary. We picture the object scene, then, as consisting of "grains" of intensity 1 placed within a field of 0s. How can the grains be properly placed in order to effect a restoration?

---

*B.R. Frieden and C.K. Zoltani, "Maximum Bounded Entropy: Application to Tomographic Reconstruction," Applied Optics, Vol. 24, p. 201, 1985.

III. APPROACH

Denote the grain positions as (X_{1i}, X_{2i}, i=1,..., Nparts) where i denotes grain number, X_{1i} is that grain's row position, and X_{2i} is that grain's column position. For shorthand, denote these X-values as $\bar{X}$ where

$$\bar{X} = \{(X_i, Y_i)\}_{i=1}^{Nparts} .$$

The total number of grains Nparts may be estimated, from (1) as

$$Nparts = \sum_{i=1}^{Nfield} \sum_{j=1}^{Nfield} Data(i,j) \tag{2}$$

since, by normalization of spread function s, the right-hand side sums to

$$\sum_{k=1}^{Nfield} \sum_{m=1}^{Nfield} Obj(k,m) + \sum_{i=1}^{Nfield} \sum_{j=1}^{Nfield} Noise(i,j). \tag{3}$$

Of these two sums, the first is exactly Nparts, while the second should tend to be small compared to the first if the noise is zero-mean. In simulations using Poisson noise, it was found that the estimated Nparts value very well-approximated the true value.

With Nparts known, the following algorithm was found, after much experimentation, to work fairly well on restoring the correct $\bar{X}$ (grain position) values. Start with an initial guess at $\bar{X}$. A good guess, e.g., is the Nparts highest intensity values in the Data(i,j). Since the object is binary, this is often a very good guess. For example, if no noise were present, an object consisting of a single round shape would be perfectly restored by this initial guess! (Such is the power of the binary assumption.)

Next, perturb each grain position independently and uniformly randomly ± Excurs, where Excurs is an integer input number. Motion is allowed in both coordinate directions. For example, we used Excurs = 20 when the image size was Nfield = 64. Accept the new grain position if (a) it was unoccupied (keeping the object binary), and (b) image inconsistency (defined below) is reduced, and (c) a "clump" penalty is satisfied (as defined below) if the penalty is turned on.

Image inconsistency Y is defined as

$$Y = \sum_{i=1}^{Nfield} \sum_{j=1}^{Nfield} [Run(i,j) - Data(i,j)]^2, \tag{4a}$$

where Run(i,j) is the running image defined as convolution of the running object Abj(k,m) with the point spread function

$$Run(i,j) = \sum_{k=1}^{Nfield} \sum_{m=1}^{Nfield} Abj(k,m)s(i-k, j-m). \tag{4b}$$

The running object Abj is the updated object formed from $\overline{X}$ with the possibly perturbed grain position incorporated.

Thus, if Y is decreased, this means that the grain in question was placed in a position that is more consistent with the image data, and hence, probably a correct object position. Therefore, the test position is accepted, and $\overline{X}$ is updated. Next, particle number i is incremented, and a new particle is perturbed in position, the next Y again tested, etc.

If a particle fails one of the tests (a)-(c), it is left at its given $\overline{X}$ position, and the next particle is considered, etc. Once particle number i = Nparts is attained, a new cycle with i=1 begins, etc.

The algorithm seeks merely to minimize Y for half its allotted cycles. The clump penalty is turned off during these trials. The reason is that small object shapes will usually not be present in the initial object estimate, as they may be too weak in intensity to be counted in the Nparts highest image values. Therefore, the role of these first cycles is to get particles out to where these smaller shapes exist. But since the particles are perturbed one-by-one, they will (at first) be isolated at the new positions required. Isolated particles violate the clump penalty. Hence, it must be turned off during these cycles.

The clump penalty is defined as

$$C = \sum_{i=1}^{Nparts} c_i, \tag{5}$$

where

$$c_i = \begin{cases} 1 \text{ if particle i has less than Nclump nearest neighbors} \\ 0 \text{ if particle i has at least Nclump nearest neighbors.} \end{cases}$$

The nearest neighbor positions for a particle at position (x,y) are all nine positions ($x \pm \Delta x$, $y \pm \Delta y$); $\Delta x = 0,1$, $\Delta y = 0,1$. Nclump is an input parameter governing the size of the minimal object shape. A value Nclump = 1 effectively turns off the clump penalty since any particle has at least itself as a nearest-neighbor. When the clump penalty was turned on, values Nclump = 3 or 4 were used, depending upon the stage of the cycle number. This is described next.

After half the specified number of cycles are complete, the running object usually is fairly well approximated. Even the smaller shapes have particles in their vicinity. However, some particles will be pushed out randomly to near the margin regions, and in general, many isolated particles will exist. At this point, a "merge" operation is performed whereby each particle that is isolated is merged with its nearest object clump, thereby satisfying the clump constraint. The operation is as follows: (1) each particle is tagged as being either isolated or "clumped"; (2) the closest "clumped" particle to a given isolated particle is found; (3) all unoccupied nearest-neighbor sites to the clumped particle are found; (4) the candidate unoccupied location that would reduce Y the most is found; and (5) the

isolated particle is placed in that position. The particle is now no longer isolated. The next isolated particle is considered, etc.

The cycling as above now proceeds anew using Nclump = 3 and Excurs = 5 (reduced) for the next remaining 1/4 cycles. Excurs is reduced because at this stage the particles are presumed fairly near their correct positions. The total penalty used is now Y+C. Again, only particle positions are accepted which reduce the total penalty. This keeps the particles in clumps of at least size 3, as required, while further reducing image inconsistency.

Next, during the last 1/4 cycles, values Nclump = 3 (as before) and Excurs = 3 (reduced) are used. Excurs is so reduced because the particles are presumed even closer to their correct positions at this stage.

Finally, after the last cycle, a "creep" or "touchup" step is performed. This step is meant to move irregularly placed particles on the contour of the object shapes to more regular positions. Although these particles already obey the Nclump = 3 constraint, they are in positions which give the contour a very high degree of irregularity locally. An example is shown in Figure 1, where point A is a candidate for "creep." Intuitively, it seems instead to belong at the unoccupied (black) site to its lower left, completing the triangle. Interestingly, this intuition can be quantified. In its present position, point A satisfies Nclump = 3 (just) but not Nclump = 4. On the other hand, all other particles shown satisfy Nclump = 4 except for particle B. Therefore, particles A and B are made candidates for "creep." This operation moves the particle to the neighborhood of the closed "clumped" particle obeying Nclump = 4, and then, into the nearest neighbor unoccupied site to the clumped particle that reduces Y the most. If Y can only be increased by making the move, it is not made. The effect upon Figure 1 is as follows. If the object had the trianglar shape shown, then moving particle A into the black site would reduce image inconsistency. Hence, "creep" will perform this move. However, no move of particle B would reduce image inconsistency. It already is in the right place. Hence, "creep" leaves B where it was (correctly).

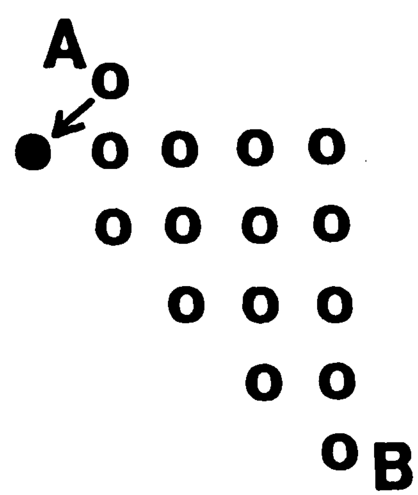


Figure 1. Binary Object Representation and Particle Movement.

A flow diagram of the total algorithm is shown in Figure 2.

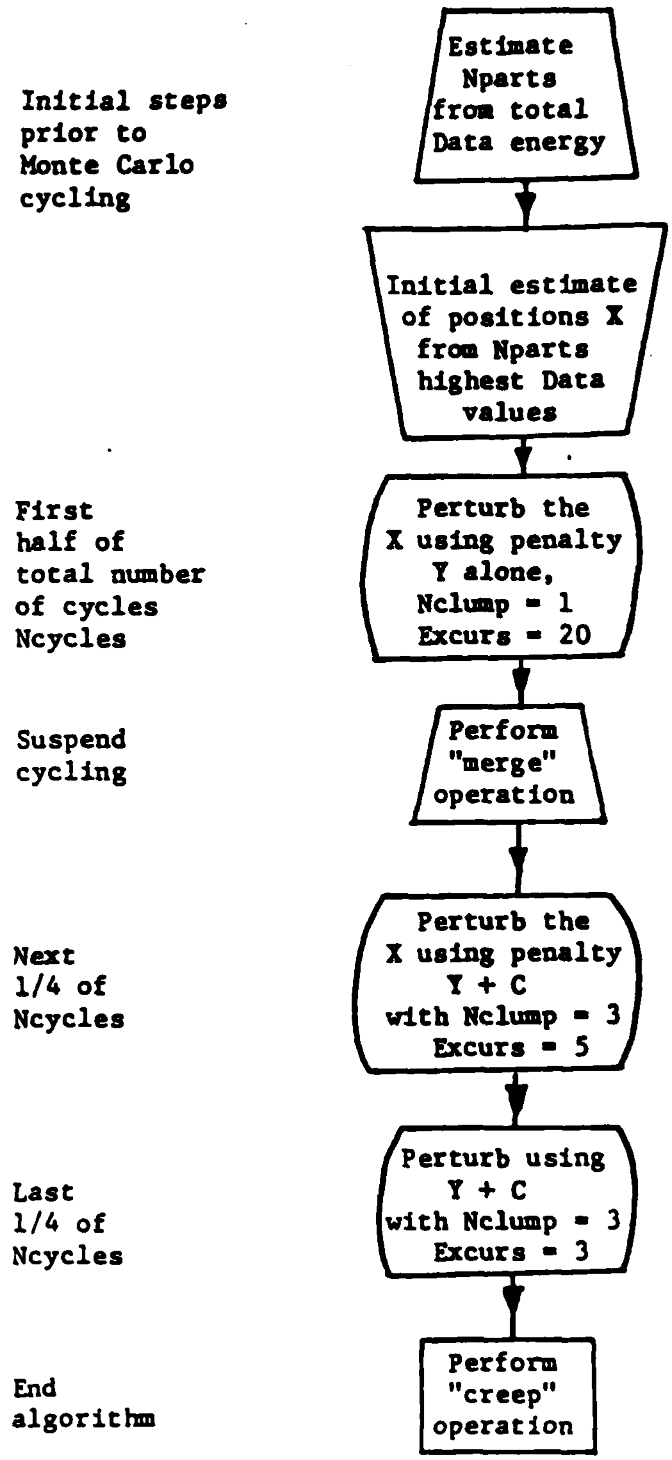
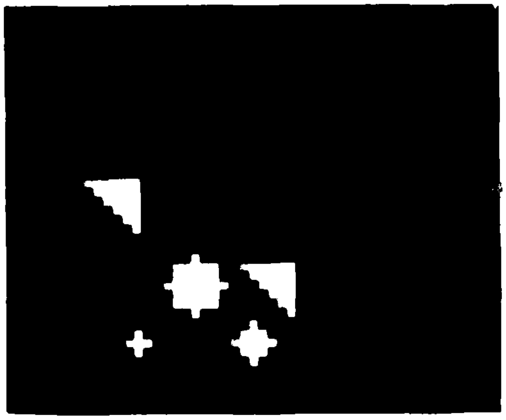


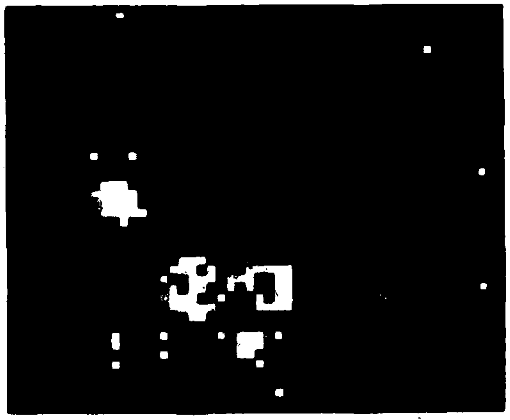
Figure 2. Flow Diagram of the Deblurring Algorithm.

IV. RESULTS

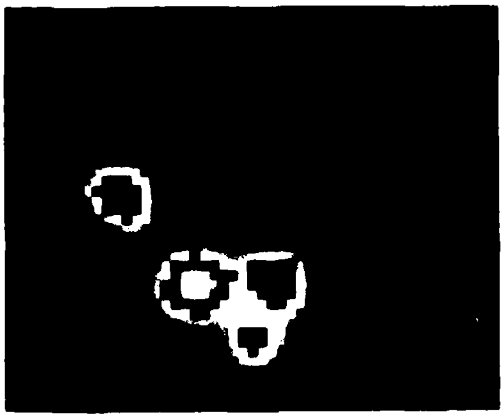
The power and the limitations of the algorithm is illustrated in Figure 3. There, in the top left panel, the original image is shown. Below, the "blurred" image is displayed in binary form. The signal to noise ratio in the image data is 100. The succeeding panels on the right show the image improvement after 100 and 600 computational cycles. A noticeable improvement in the image definition is apparent. Work is underway to extend the technique to multi-grey level images, as well as where large pixel numbers must be considered. Typical running time on a CDC Cyber 76, for an image field consisting of 4096 pixels, is currently 1056 CPU seconds.



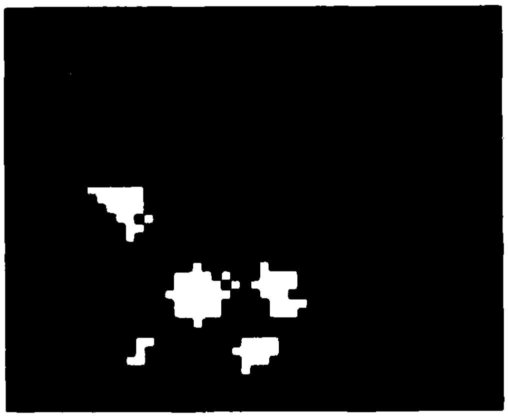
a. Original Image



c. Image After 100 Iterations



b. Blurred, i.e., Original Convolved With a PSF



d. Image after 600 Iterations

Figure 3. Deblurring an Object with Sharp Corners.

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